

# Single top production at the Tevatron and the LHC

Durham, May 2006

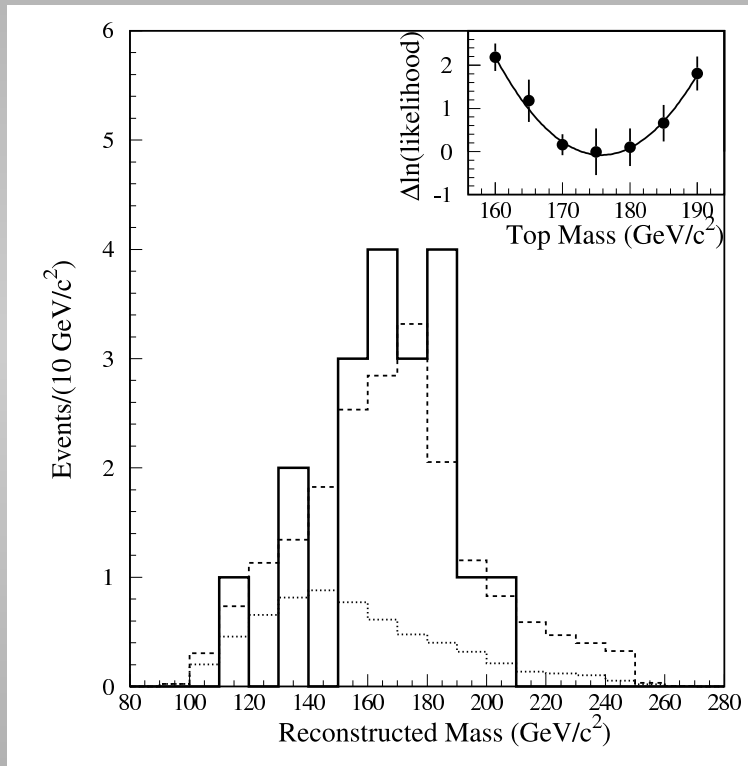
John Campbell  
*University of Glasgow*

# *Outline*

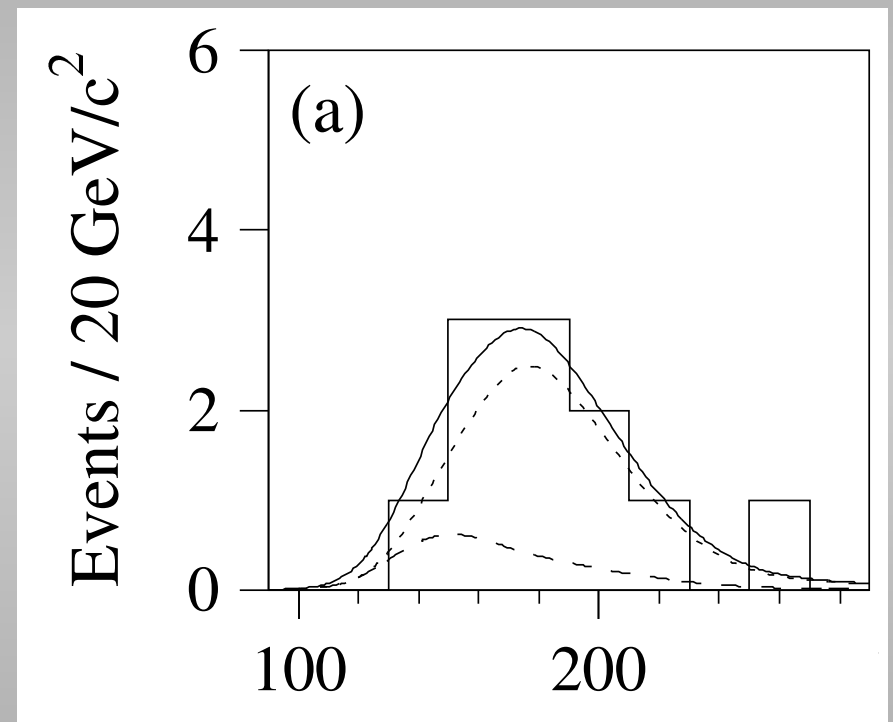
- Top quark production at hadron colliders.
- Single top calculations.
- Implementation of top quark production and decay.
- Tevatron phenomenology.
- Associated production at the LHC.
- Conclusions.

# Discovery

- The discovery of the top quark in 1995 completed the picture of quarks in the Standard Model.



CDF, hep-ex/9503002

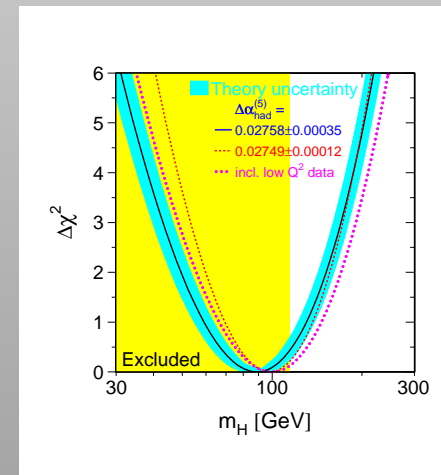
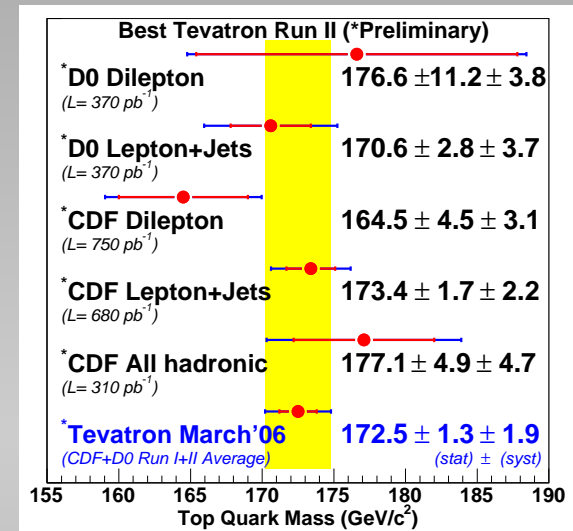


D0, hep-ex/9503003

- Discovery was in the pair production channel, with leptonic decay of the top. Despite the small sample of events ( $37 + 18$ ) and large errors on the mass and the estimate of the cross section, the central values have not changed much since.

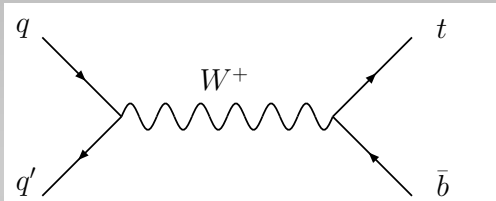
# Precision measurement

- The latest measurements from CDF and D0 are based on more than  $1 \text{ fb}^{-1}$  of data (combined) and benefit from the slightly higher available energy in Run II.
- Mass measurements are now available in all  $W$  decay channels, with broadly consistent results.
- The measured cross section agrees well with NLO+resummed calculations.
- By the end of Run II, the combined precision on  $m_t$  should be less than 1%.
- By combining with the  $W$  mass measurement, these results give clues to the mass of a SM Higgs. The preferred value of  $m_H$  is less than  $\approx 130 \text{ GeV}$  and we would reasonably expect  $m_H < 175 \text{ GeV}$ .



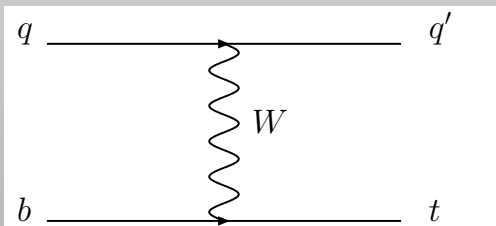
# Single top production

- As well as pair-producing the top quark via the strong interaction, a top quark can be produced singly via the weak interaction.
- There are three such mechanisms, which provide different probes of both the physics of the top quark and possible new physics beyond the SM.



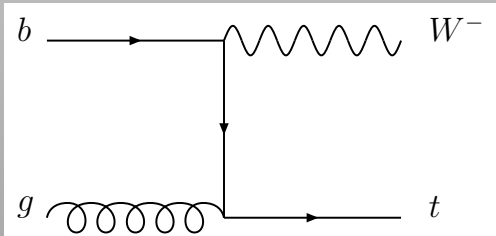
## *s*-channel

sensitive to new heavy resonances/flavour changing charged currents



## *t*-channel

direct measurement of  $V_{tb}$  and the partial decay width  $\Gamma(t \rightarrow Wb)$

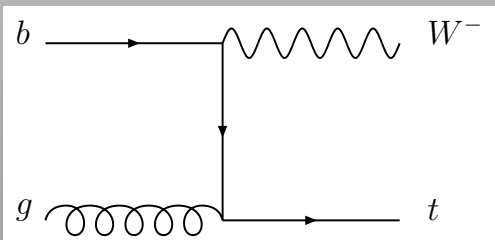
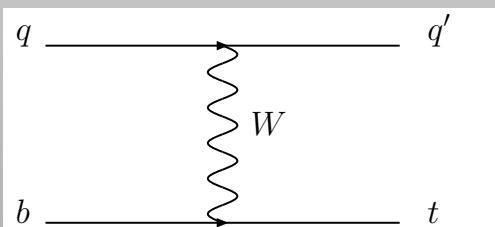
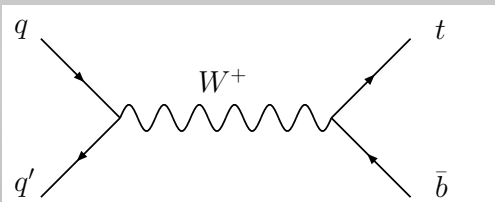
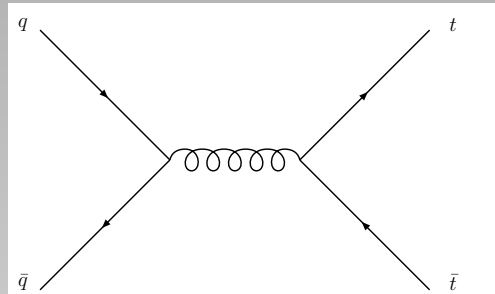


## *Wt* production

$V_{tb}$  and FCC couplings

- In addition, at the LHC these processes can provide significant backgrounds in other analyses.

# Top production rates



Tevatron

LHC

6pb

720 pb

0.8 pb

10 pb

1.8 pb

240 pb

0.14pb

66 pb

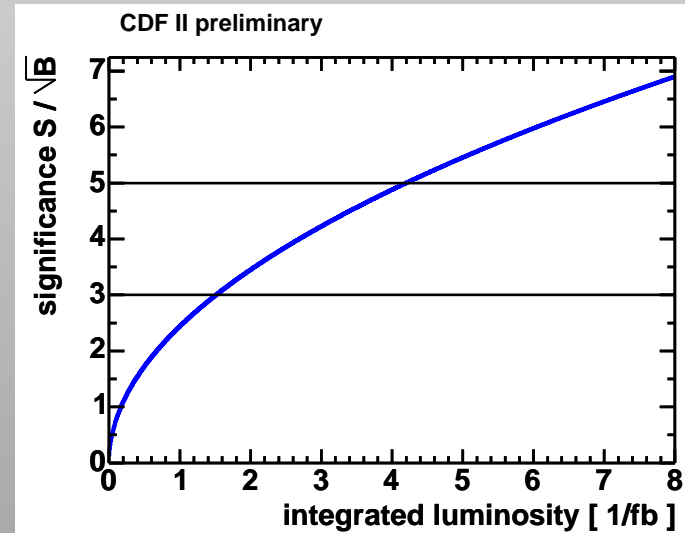
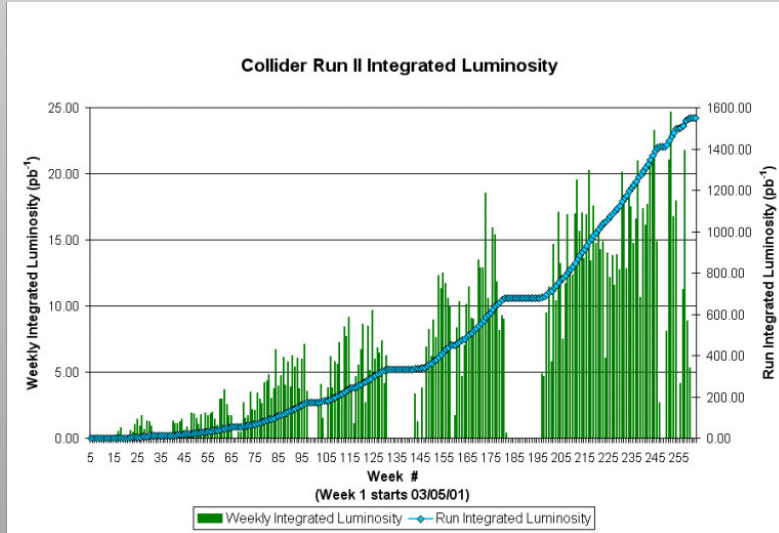
# Single top search at the Tevatron

- So far, single top production has not been observed at the Tevatron.
- Instead, only 95% limits can be placed on the combined cross sections:

$$\sigma(s - \text{channel}) < 3.2 \text{ pb (CDF)}, 5.0 \text{ pb (D0)}$$

$$\sigma(t - \text{channel}) < 3.1 \text{ pb (CDF)}, 4.4 \text{ pb (D0)}$$

to be compared with the expected cross sections of 0.89 pb ( $s$ ) and 1.98 pb ( $t$ ).



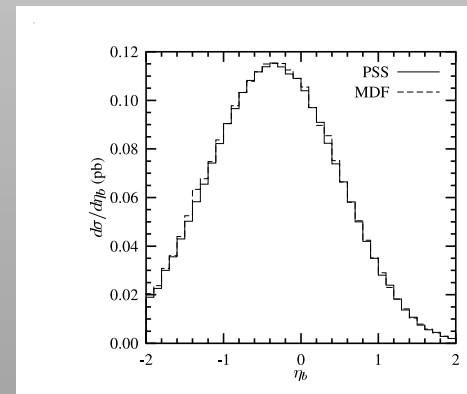
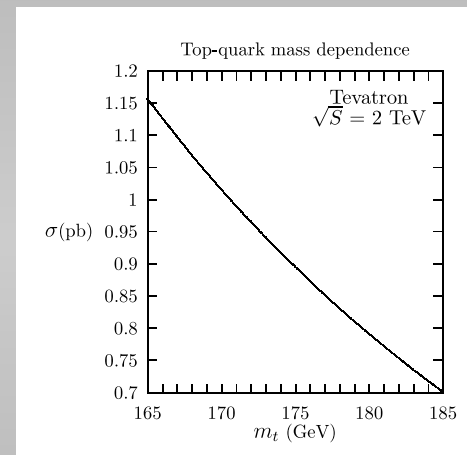
- Discovery of these channels should be right around the corner.

# History of single top calculations



## Previous studies

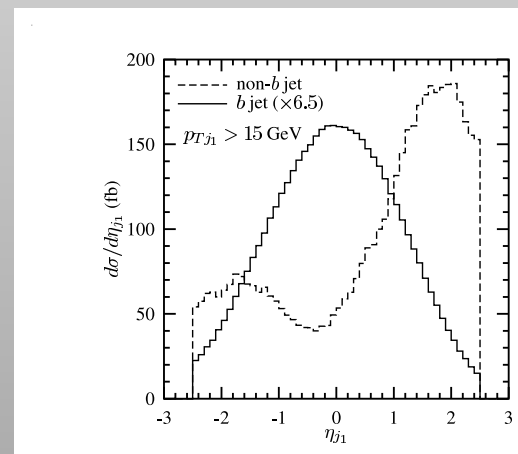
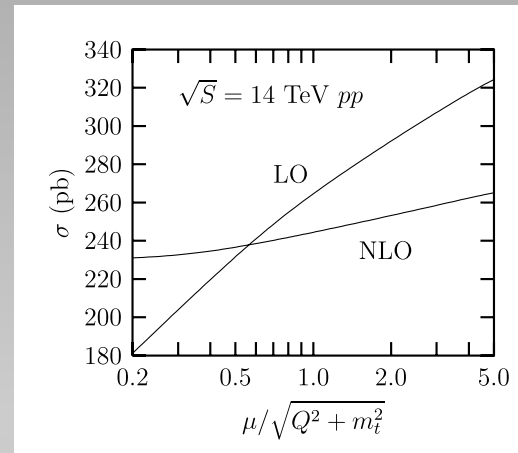
- When including  $O(\alpha_s)$  corrections and working at next-to-leading order, the dependence on renormalization and factorization scales is expected to be mild.
- Therefore the first serious estimate of a cross section in QCD is obtained at this order.
- $s$ -channel:
  - ★ NLO corrections to the inclusive process in 1996.  
Smith, Willenbrock
  - ★ Limited to the total cross section.
  - ★ The effect of NLO on differential distributions came later, in 2002.  
Harris, Laenen, Phaf, Sullivan, Weinzierl
  - ★ Some experimental cuts can be applied, although the top quark is still considered a stable particle.
  - ★ Predictions for quantities such as the transverse momentum and rapidity of the  $b$ -quark are possible.



# Previous studies

## ■ $t$ -channel:

- ★ First inclusive calculation in 1995.  
Bordes, van Eijk
- ★ The calculation was performed in the DIS scheme. However the CTEQ  $b$ -quark used was not compatible with this scheme, yielding flawed results.  
Stelzer, Sullivan, Willenbrock
- ★ A more differential calculation appeared together with the  $s$ -channel one.  
Harris, Laenen, Phaf, Sullivan, Weinzierl
- ★ Detailed studies of the effect of jet-finding algorithms, tagging and comparison with HERWIG and PYTHIA possible.  
Sullivan



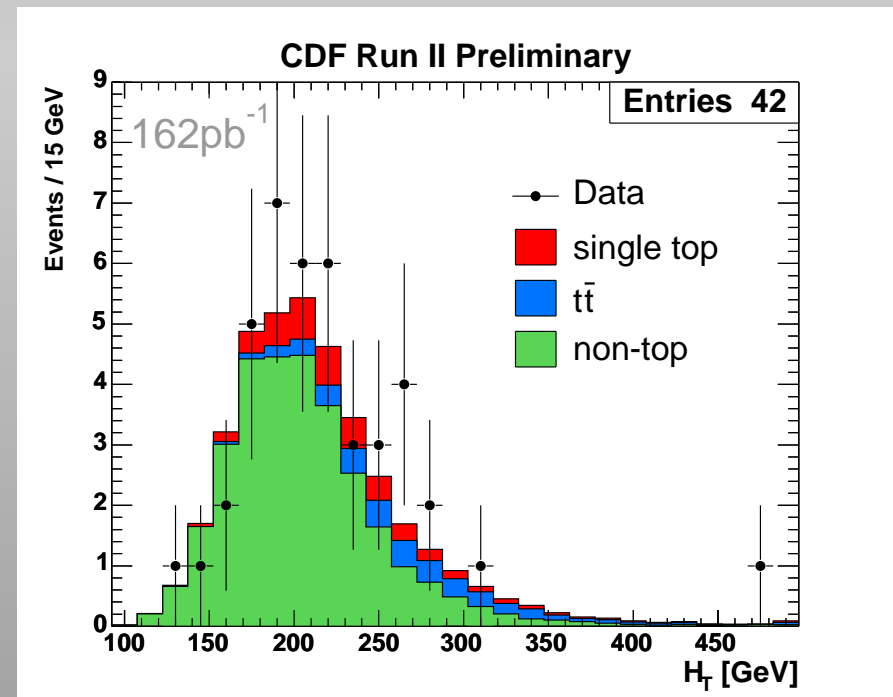
## *Previous studies*

### ■ $Wt$ production:

- ★ Extensive consideration at leading order, in particular with regard to the relationship with the  $t\bar{t}$  process.  
Belyaev, Boos, Dudko; Tait
- ★ Fully differential NLO corrections to the very similar  $Wc$  process.  
Giele, Keller, Laenen
- ★ Differential calculation of the  $Wt$  process in 2002.  
Zhu
- ★ No decays of the  $W$  or top quark are included. The only results presented in the paper are inclusive cross sections and no program is available.
- ★ Results appear to be somewhat overlooked in the subsequent literature.

# The need for decays

- The effect of NLO corrections can be to change the shapes of distributions such as the  $p_T$  and  $\eta$  of particles in the final state.
- Therefore in a given analysis, both the cut efficiency and the observable being studied can change at NLO.
- In order to match an experimental study as closely as possible and make the most of the power of NLO, a study including as much of the decays as possible is preferred.
- This is highlighted by the search at the Tevatron, where  $H_T$  is a discriminator between signal and background events.
- $H_T$  is the scalar sum of the transverse momenta of all final state particles: leptons, jets and missing energy.
- Impossible to predict the effect of NLO on this distribution without knowledge of the top decay.



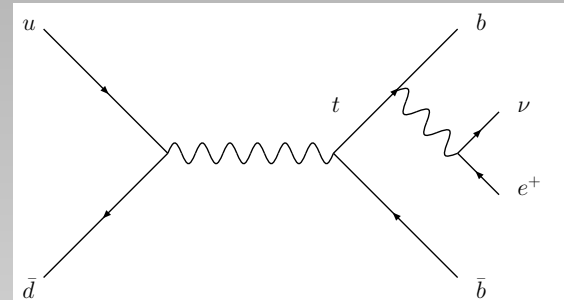
# Outline of the calculation

# Processes considered

- Include the leptonic decay of the top quark, retaining all spin correlation information.

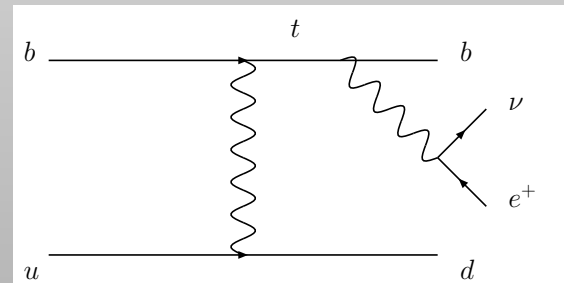
- $s$ -channel production

$$u + \bar{d} \rightarrow t + \bar{b} \rightarrow \nu + e^+ + b$$



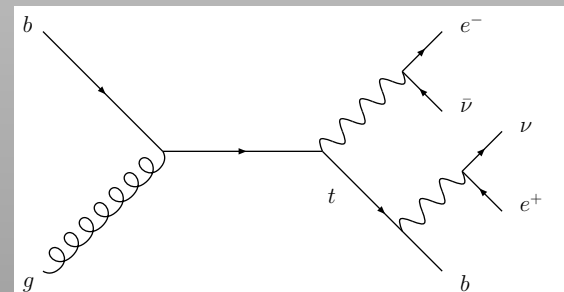
- $t$ -channel production,

$$b + u \rightarrow t + d \rightarrow \nu + e^+ + b$$



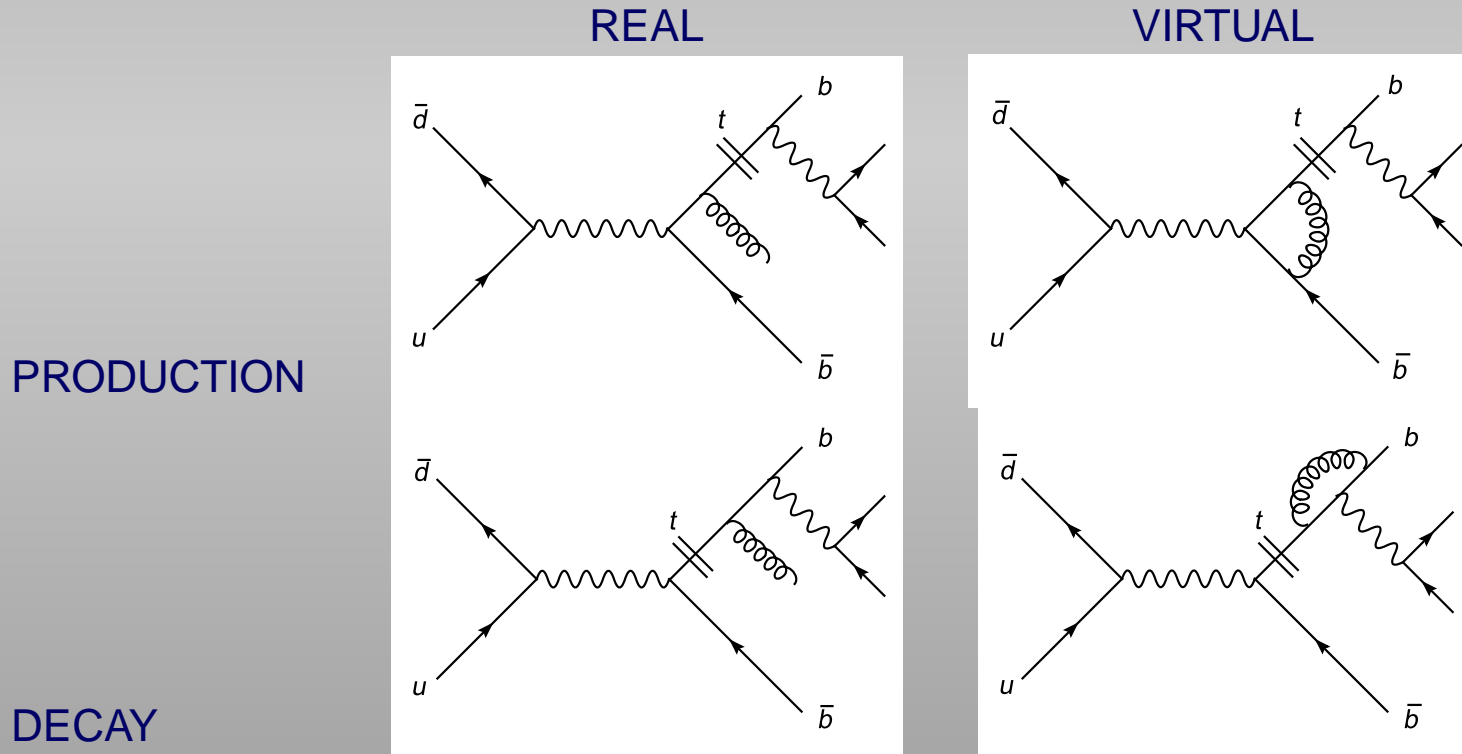
- associated  $Wt$  production

$$b + g \rightarrow W^- + t \rightarrow \begin{cases} \nu + e^+ + b \\ e^- + \bar{\nu} \end{cases}$$



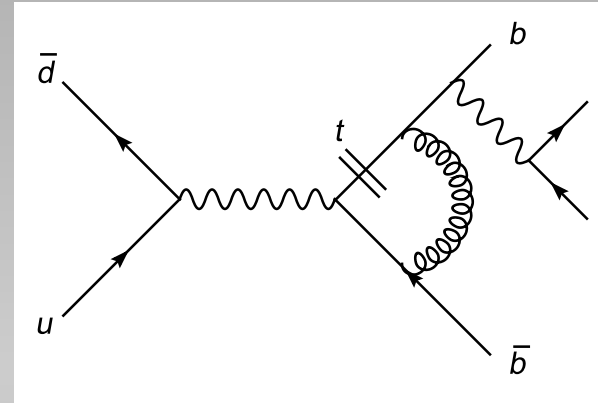
# Production and decay radiation

- Divide the real and virtual corrections into two categories: radiation associated with the production and decay stages of the top quark.
- The double bar indicates the separation of the two stages by a top quark which is on its mass shell. Diagrams without an on-shell top are suppressed by  $\Gamma_t/m_t$ .



# Neglected diagrams

- The separation into production and decay stages in this way ensures that the final result is gauge invariant.
- However, we have neglected interference between radiation in the two stages.
- This interference occurs both in the real and the virtual contributions.



- The physical argument for neglecting these terms is based on the difference between the characteristic time scales:

$$\text{production of } t\bar{b}: 1/m_t, \quad \text{decay of top: } 1/\Gamma_t.$$

Fadin, Khoze, Martin; Melnikov, Yakovlev

- In general, the two stages are separated by a large time and interference effects average to zero. In the soft region real and virtual radiation cancels.
- We expect an effect of order  $\alpha_s \Gamma_t / m_t \sim$  a few percent. This is confirmed by studies of the  $s$ -channel process and in top pair production in  $e^+e^-$  annihilation.

Pittau; Macesanu



# Implementation

- Soft and collinear contributions in the real matrix elements are cancelled using the dipole subtraction method for massive particles.

Catani, Dittmaier, Seymour, Trocsanyi

- A further generalization of the original dipole method introduces a tuneable parameter which controls the size of the subtraction region – only the singular regions require the subtraction.

Nagy, Trocsanyi

- The calculation includes an extension of the massive dipole method to include such parameters for each class of dipole.
- These parameters are useful in a number of ways:
  - ★ Varying  $0 < \alpha \leq 1$  (default) is a good check of the calculation.
  - ★ Reducing  $\alpha$  increases the real contribution (less is subtracted) and decreases the contribution from the virtual diagrams and counterterms.

$$\tilde{\mathcal{V}}^{g,q}(x; \epsilon, \alpha) = T_R \left( (1-x)^2 + x^2 \right) \left[ 2 \ln(1-x) - \frac{1}{\epsilon} + \Theta(1-x-\alpha) \ln \left( \frac{\alpha}{1-x} \right) \right]$$

- ★ A smaller  $\alpha$  means a more stable and quicker real radiation calculation. Empirically,  $\alpha = 0.1$  is convenient.

# Dipole for the decay

- We require a subtraction counter-term for the process,

$$t \longrightarrow W + b + g$$

- As usual, this is written as a singular function multiplied by the matrix elements for the lowest order process,

$$t \longrightarrow \widetilde{W} + \tilde{b}$$

- The kinematics must change, with the  $W$  and  $b$  momenta modified to absorb the momentum carried away by the gluon,  $\tilde{p}_W + \tilde{p}_b = p_W + p_b + p_g$ .
- To ensure that the same kinematics occur in the counter-term both particles must remain on-shell,  $\tilde{p}_W^2 = p_W^2$  and  $\tilde{p}_b^2 = p_b^2$ .
- $\tilde{p}_W$  can then be defined by a general Lorentz transformation on  $p_W$  which satisfies the constraint  $\tilde{p}_b^2 = 0$ . It reduces to,

$$\tilde{p}_W = \alpha \left( p_W - \frac{p_t \cdot p_W}{p_t^2} p_t \right) + \beta p_t$$

where the constants are given by,

$$\alpha = \frac{p_t^2 - p_W^2}{2\sqrt{(p_t \cdot p_W)^2 - p_W^2 p_t^2}}, \quad \beta = \frac{p_t^2 + p_W^2}{2p_t^2}$$

# MCFM

- All the single top calculations are included in the latest release of the general purpose partonic Monte Carlo MCFM, <http://mcfm.fnal.gov>.

JC and R.K. Ellis

(+F. Tramontano, +F. Maltoni, S. Willenbrock)

$p\bar{p} \rightarrow W^\pm / Z$	$p\bar{p} \rightarrow W^+ + W^-$
$p\bar{p} \rightarrow W^\pm + Z$	$p\bar{p} \rightarrow Z + Z$
$p\bar{p} \rightarrow W^\pm + \gamma$	$p\bar{p} \rightarrow W^\pm / Z + H$
$p\bar{p} \rightarrow W^\pm + g^* (\rightarrow b\bar{b})$	$p\bar{p} \rightarrow Z b\bar{b}$
$p\bar{p} \rightarrow W^\pm / Z + 1 \text{ jet}$	$p\bar{p} \rightarrow W^\pm / Z + 2 \text{ jets}$
$p\bar{p}(gg) \rightarrow H$	$p\bar{p}(gg) \rightarrow H + 1 \text{ jet}$
$p\bar{p}(VV) \rightarrow H + 2 \text{ jets}$	$p\bar{p} \rightarrow t + q$
$p\bar{p} \rightarrow H + b$	$p\bar{p} \rightarrow Z + b$
$p\bar{p} \rightarrow W + t$	

- Emphasis has been on bringing together calculations of signals and backgrounds for particularly challenging searches, so that NLO effects may be more easily studied with just one code.
- Where possible, appropriate decays of vector bosons are included and all possible spin correlations are retained for a better match with experimental cuts.

## Inclusion of decay

- The inclusion of QCD corrections in the decay of the top quark should not change the total cross section.
- When including the decay, the NLO width of the top quark must be used:

$$\Gamma_t = \Gamma_0 + \alpha_s \Gamma_1 \approx \Gamma_0(1 - 0.8\alpha_s)$$

so that the NLO width is about 10% lower than at LO.

- In the perturbative approach, the difference is of order  $\alpha_s^2$  and is given by,

$$\sigma B_{t \rightarrow b\nu e + X} - \sigma B_{t \rightarrow b\nu e} = \left( \frac{\Gamma_t^{LO}}{\Gamma_t^{NLO}} - 1 \right) (\sigma B_{t \rightarrow b\nu e} - \sigma_0 B_{t \rightarrow b\nu e}).$$

Process	$\sqrt{s}$ [TeV]	$\sigma_0 B_{t \rightarrow b\nu e}$ (fb)	$\sigma B_{t \rightarrow b\nu e}$ (fb)	$\sigma B_{t \rightarrow b\nu e + X}$ (fb)
$s$ -channel, $p\bar{p}$ ( $t$ )	1.96	31.5	44.6	45.9
$s$ -channel, $pp$ ( $t$ )	14	504	681	699
$t$ -channel, $p\bar{p}$ ( $t$ )	1.96	111.3	114.0	114.0
$t$ -channel, $pp$ ( $t$ )	14	17690	17050	16980
$W^- t$ , $p\bar{p}$	1.96	0.856	0.789	0.781
$W^- t$ , $pp$	14	357	392	396

- The differences agree with the expectation and are less than 3% in all cases.

# Single top at the Tevatron

# Overview

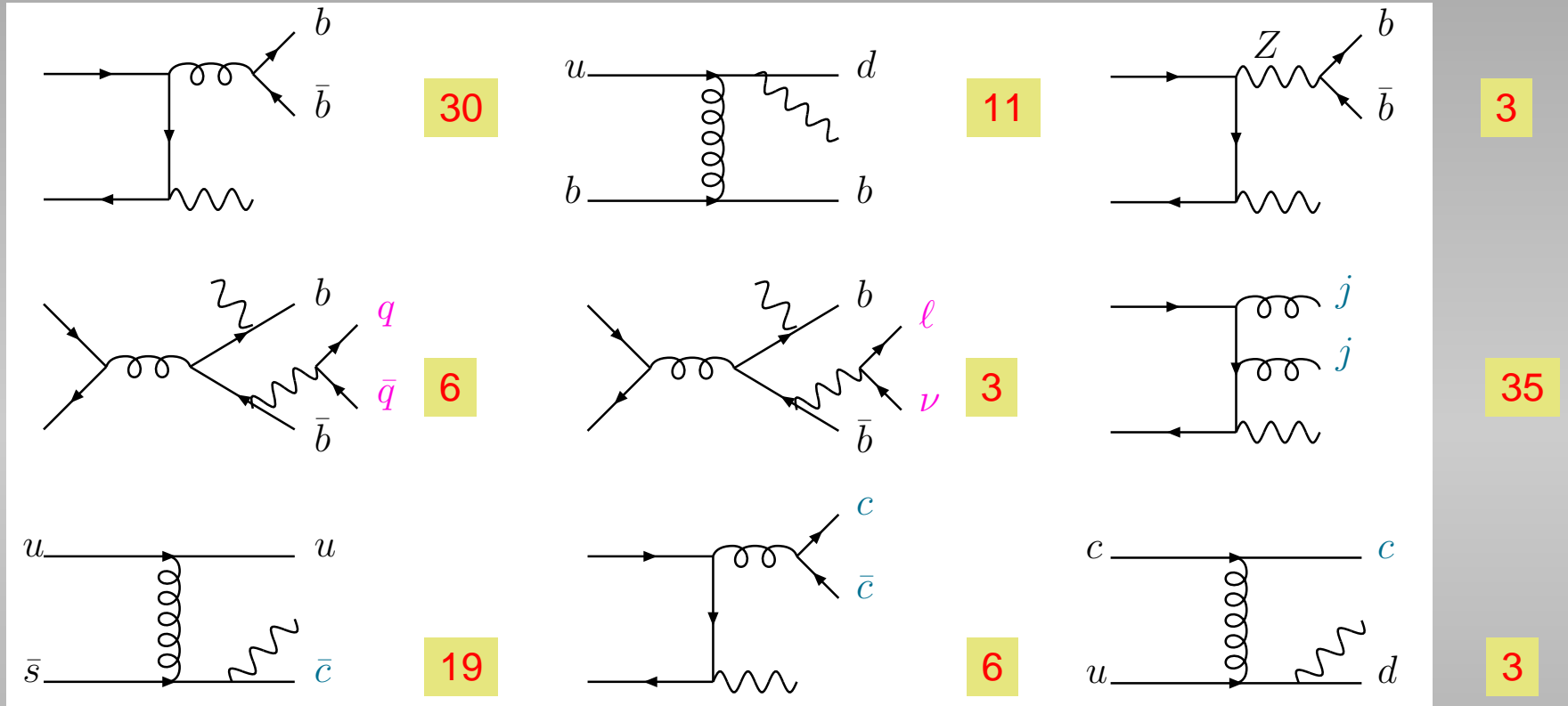
- Only the  $s$ – and  $t$ – channel processes can possibly be observed.
- The effect of NLO corrections on the total rate is an increase of around 40% for the  $s$ -channel, whilst the  $t$ -channel rate is practically unchanged.
- The final state observed in the detectors consists of a lepton, missing energy and two jets – one of which is  $b$ -tagged.
- Exploit the ability to observe all decay products by matching the cuts used in the searches at CDF and D0 as closely as possible:

$$p_T^e > 20 \text{ GeV}, \quad |\eta^e| < 1.1, \quad \cancel{E}_T > 20 \text{ GeV},$$

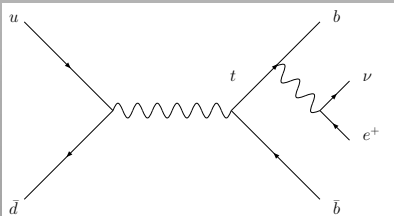
$$p_T^{\text{jet}} > 15 \text{ GeV}, \quad |\eta^{\text{jet}}| < 2.8, \quad \Delta R^{jj} > 1.0.$$

- There is a plethora of backgrounds, the largest coming from  $Wb\bar{b}$  events. Further substantial contributions are the result of mis-identifying a charm quark as a bottom jet.
- The rate of most of these backgrounds can be estimated at NLO using the program MCFM.

# Event rates



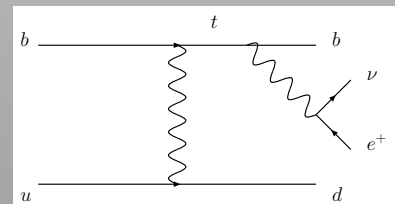
■ Cross-sections in fb include nominal tagging efficiencies and fake rates.



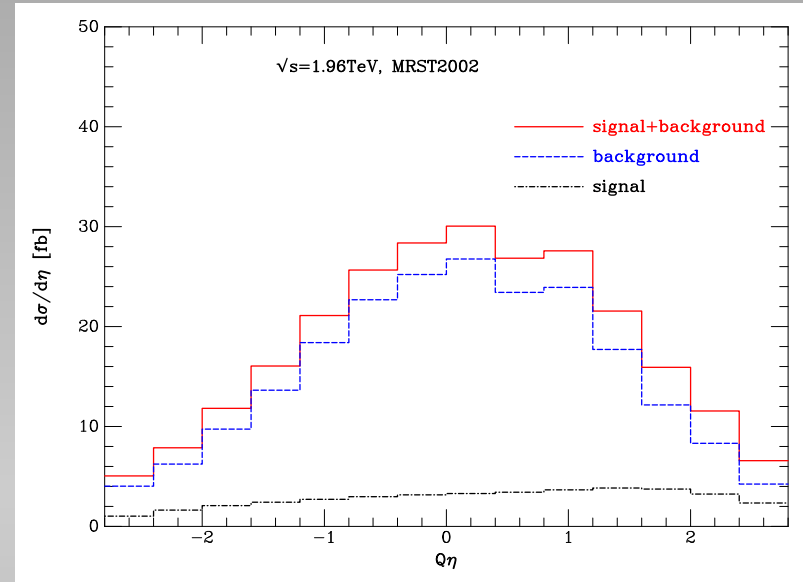
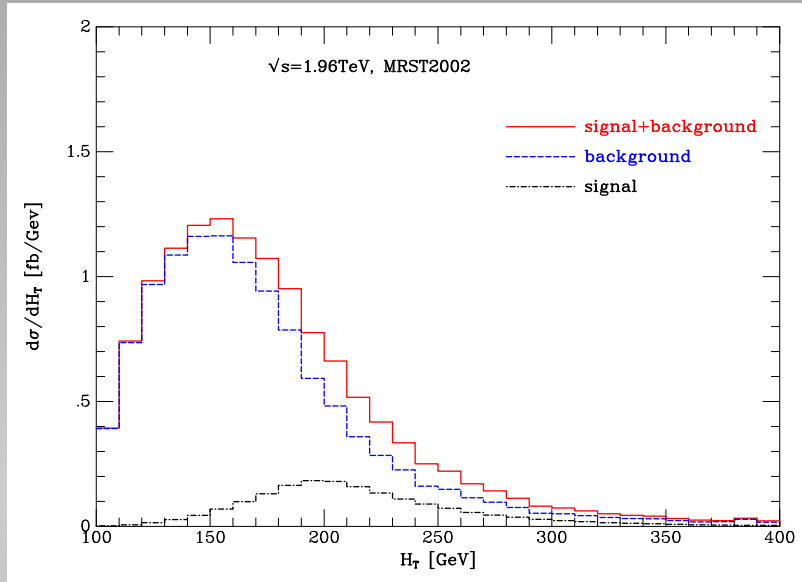
signal rates

**7 fb**

**11 fb**



# Single top signal vs. backgrounds



- $H_T$  = scalar sum of jet, lepton and missing  $E_T$ .
- $Q_\eta$  is the product of the lepton charge and the rapidity of the untagged jet, useful for picking out the  $t$ -channel process ( $b + u \rightarrow W^+ b + d$ ).
- Signal:Background (with our nominal efficiencies) is about 1 : 6  
– a very challenging measurement indeed. It's not so surprising that this mode has not yet been observed at Fermilab.
- Refining the shape of the QCD predictions will help pin down the single top channels soon.

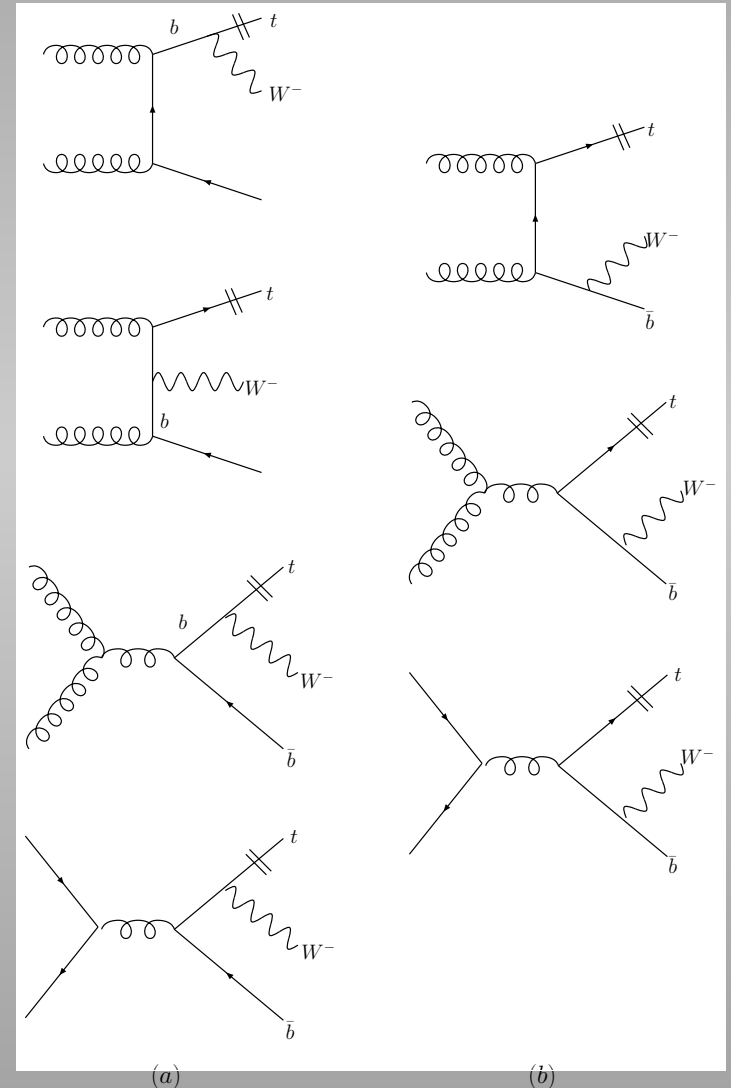


# $Wt$ production at the LHC

# Resonant complications

- Most details of the calculation proceed as before.
- NLO real radiation corrections contain the process  $gg \rightarrow Wtb$ . This final state is also obtained by producing two top quarks on shell, one of which then decays into  $Wb$ .
- Including this contribution doesn't give a meaningful result, neither theoretically nor experimentally.
- $\sigma_{LO}(t\bar{t}) \gg \sigma_{LO}(Wt)$ , so the NLO correction would be huge.
- Keeping the two separate enables as much of the LO picture as possible to go through in a familiar way.
- An alternative approach, of not distinguishing between the two, would anyway create large logarithms  $\sim \log[m_b/(m_t + m_W)]$  and be restricted to LO at present.

Kauer, Zeppenfeld

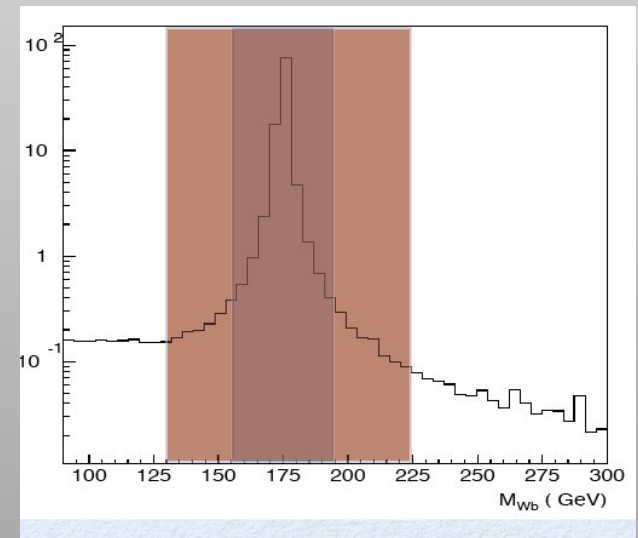


## Previous suggestions

- (Tait) Subtract the contribution from the resonant diagrams:

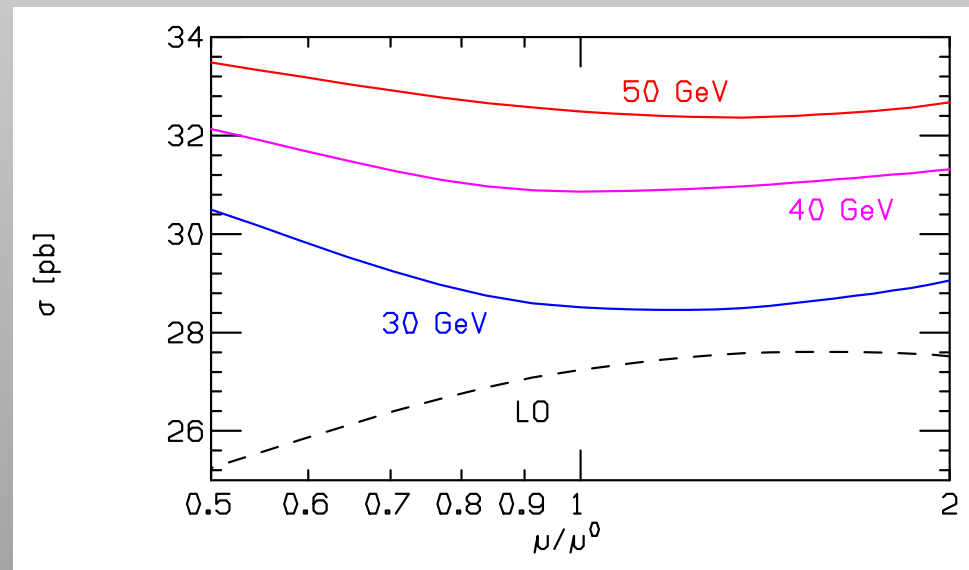
$$\sigma(gg \rightarrow Wtb)_{\text{single top}} = \sigma(gg \rightarrow Wtb)_{\text{total}} - \sigma_{\text{LO}}(gg \rightarrow t\bar{t})\text{Br}(\bar{t} \rightarrow W^- \bar{b})$$

- The problem with such an analytic approach is that it is not suitable in our Monte Carlo implementation; moreover, it is limited to the zero width approximation for the top quark.
- (Belyaev, Boos) Construct a mass window around the putative  $\bar{t}$  peak and remove any contribution inside.
- For a mass window of about  $15\Gamma_t \approx 25$  GeV, this procedure agrees with the one above.
- It is a generator-friendly approach, but heavily dependent upon the mass window chosen. This is largely because of the interference between the  $t\bar{t}$  and  $Wt$  diagrams.



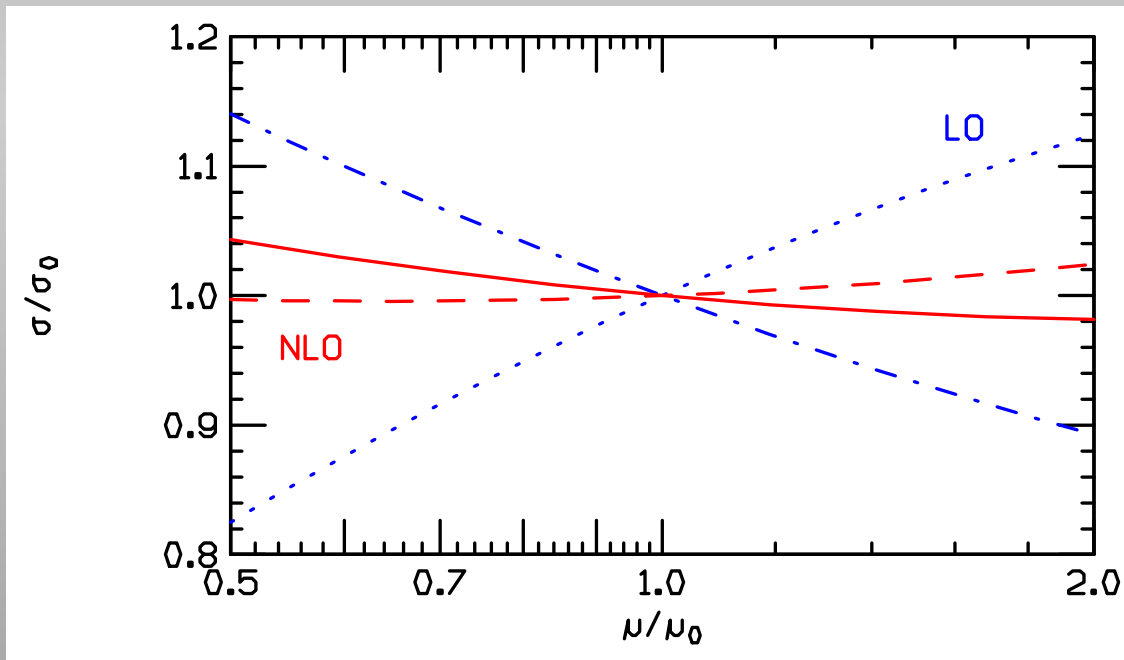
# Solution

- The contribution from the  $Wt$ -like diagrams when the  $\bar{b}$  quark  $p_T$  is small is already accounted for by the  $b$ -quark PDF. This description is accurate up to a  $p_T$  of about 60 GeV. Hence the factorization scale should be no larger than this.  
Boos, Plehn
- When the  $b$  quark  $p_T$  is large, the event should be best described by resonant  $t\bar{t}$  production anyway.
- Therefore, define the  $Wt$  process by demanding that no  $b$  quark be observed above a given value of  $p_T = \mu_V$ . Factorization and renormalization scales should also be chosen equal to  $\mu_V$ .
- The contribution from resonant  $t\bar{t}$  diagrams can be dropped (and dealt with separately) since interference terms are now negligible.
- As a result, the NLO prediction depends on the value chosen for  $\mu_V$ .
- Once accounted for in this way, the corrections are mild.



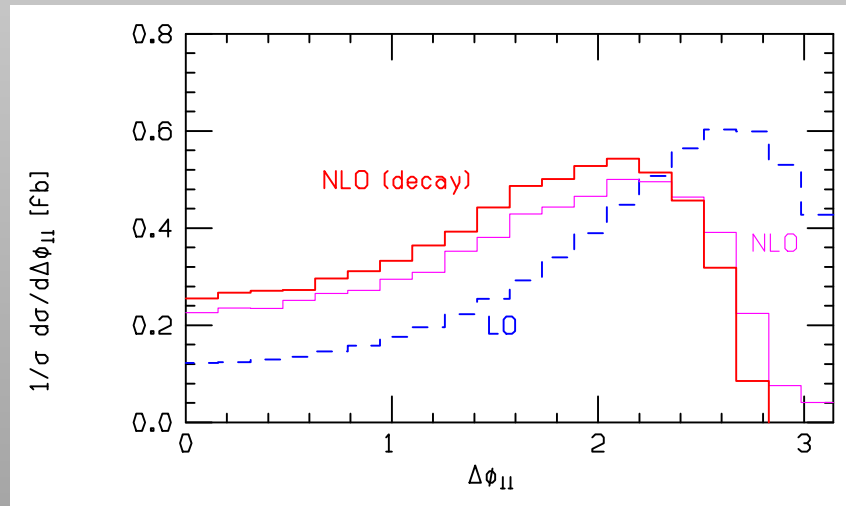
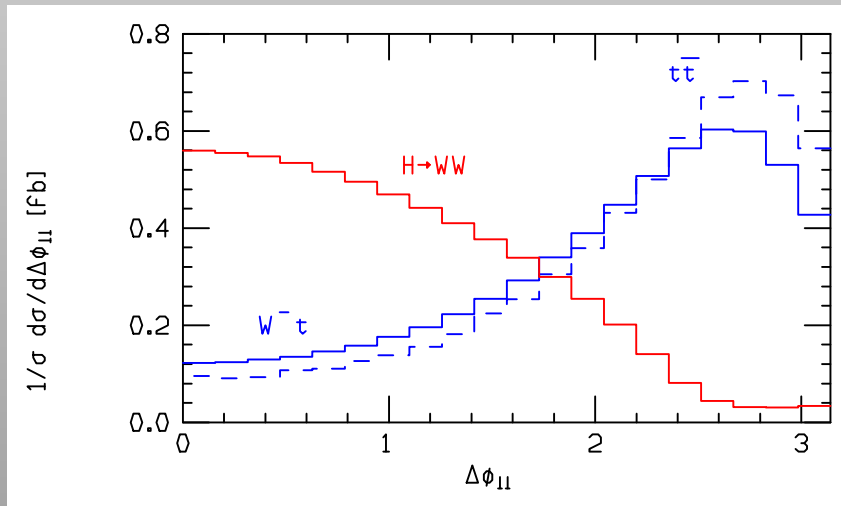
# Scale dependence

- For reasonable choices of scale, NLO corrections to the total rate are small and of the order of 5–15%.
- The dependence upon the renormalization and factorization scales at first appears to be not much better, when they are varied together. This is the result of an accidental cancellation between the two at leading order.



## Application: $gg \rightarrow H \rightarrow WW^*$

- In the mass range  $155 < m_H < 180$  GeV, the Higgs decays primarily to pairs of  $W$ 's. If the  $W$ 's decay leptonically, the Higgs signal is two leptons and missing  $E_T$ .
- The main background is from continuum  $W$  pair production, via  $q\bar{q}$  scattering and loop-induced gluon-gluon fusion.
- There are further backgrounds from events containing leptonically-decaying top quarks where the jets are not observed.
- The signal can be enhanced by using strong cuts. The opening angle between the leptons in the transverse plane ( $\Delta\phi_{\ell\ell}$ ) is a good discriminator.



# Shortcomings

The approach in MCFM involves a number of approximations:

- The  $b$ -quark is massless  
LO calculation with  $m_b = 4.75 \text{ GeV} \longrightarrow < 1\% \text{ effect}$
- The top quark is put on its mass-shell  
LO calculation with a Breit-Wigner  $\longrightarrow 1\% \text{ effect}$
- We neglect interference between radiation in production/decay  
qualitative argument for  $\mathcal{O}(\alpha_s \Gamma_t / m_t) \sim \text{less than a percent}$
- We assume  $p_T$ -independent heavy flavour tagging efficiencies, as well as stable  $b$  and  $c$  quarks  
easily addressed by a more detailed experimental analysis  
with the publicly-available code
- No showering or hadronization is performed  
the large cone size  $\Delta R = 1$  should help minimize these effects;  
recent merging of NLO and the Herwig parton shower in MC@NLO  
Frixione, Laenen, Motylinski, Webber

# Summary

- The study of single top quark production is just about to begin in earnest, with the first evidence from the Tevatron expected later this year.
- NLO predictions including decays, spin correlations and the effect of radiation in the top quark decay are now available in all channels as part of the program MCFM.
- Given the very large backgrounds at the Tevatron, such predictions should be invaluable in interpreting the data.
- At the LHC, a careful treatment of these channels is required due to their important role as backgrounds in other searches.
- In particular, the treatment of  $Wt$  production is dependent upon a careful definition of what is meant by 'single top'